

## 4. HIGH-LUMINOSITY COLLIDER R&D

The worldwide high-energy physics community has active research programs in two main areas—the energy frontier and the intensity (or luminosity) frontier. The former experimental thrust is represented by the experiments being carried out at the Fermilab Tevatron and the Large Electron-Positron (LEP) Collider, and those planned for the Large Hadron Collider (LHC). The latter program is embodied in the research to be carried out at the so-called particle factories, of which both  $B$  and  $\phi$  factories (PEP-II and KEKB, and DAΦNE, respectively) are now under construction. The factories are so-named to connote the copious quantities of particles they are designed to produce and the factory-like reliability that is necessary to ensure this.

Due to its proximity to LBNL, our group's interest has naturally focused on the PEP-II Asymmetric  $B$  Factory, being constructed by a collaboration of LBNL, the Stanford Linear Accelerator Center (SLAC), and Lawrence Livermore National Laboratory (LLNL). The *raison d'être* of PEP-II—the study of  $B$ -meson decays—will be one of the key elements of worldwide high-energy physics investigations for many years to come. Such studies are presently limited by the relatively low rate of events produced at  $e^+e^-$  storage rings such as the Cornell Electron Storage Ring (CESR). To study the most interesting processes within the Standard Model—rare decays and especially the phenomenon of charge-conjugation-parity (CP) violation—an effective increase in the event rate of at least a factor of 100 is required. Both PEP-II and KEKB achieve these higher event rates by increasing the luminosity by a factor of 10 compared with present-day machines and by simultaneously enhancing the event sensitivity through the use of energy-asymmetric collisions (equivalent to another factor of 10 in luminosity). With a peak luminosity of  $3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ , PEP-II will conduct a research program to determine the origins of CP symmetry violation in the  $B$ -meson system, the ultimate goals being a better understanding of the Standard Model and possibly an explanation of why the universe is dominated by matter rather than antimatter. An equivalent effort will be mounted at KEKB.

As shown in Figure 4-1, PEP-II will be built in the tunnel of the old Positron-Electron Project (PEP) collider that was built at SLAC in the mid-1970s by a SLAC-LBNL collaboration. LBNL physicists have major responsibility for design and commissioning of the PEP-II low-energy ring (LER), and hold major roles in the rf and feedback system groups as well. The LER of PEP-II will be one of the most challenging storage rings ever built and great care must be taken in its design and implementation. Accelerator physics is one of AFRD's prime contributions to PEP-

II, drawing upon our historical expertise in machine design, modeling and control of beam behavior, etc. (See also the Center for Beam Physics chapter of this report.)

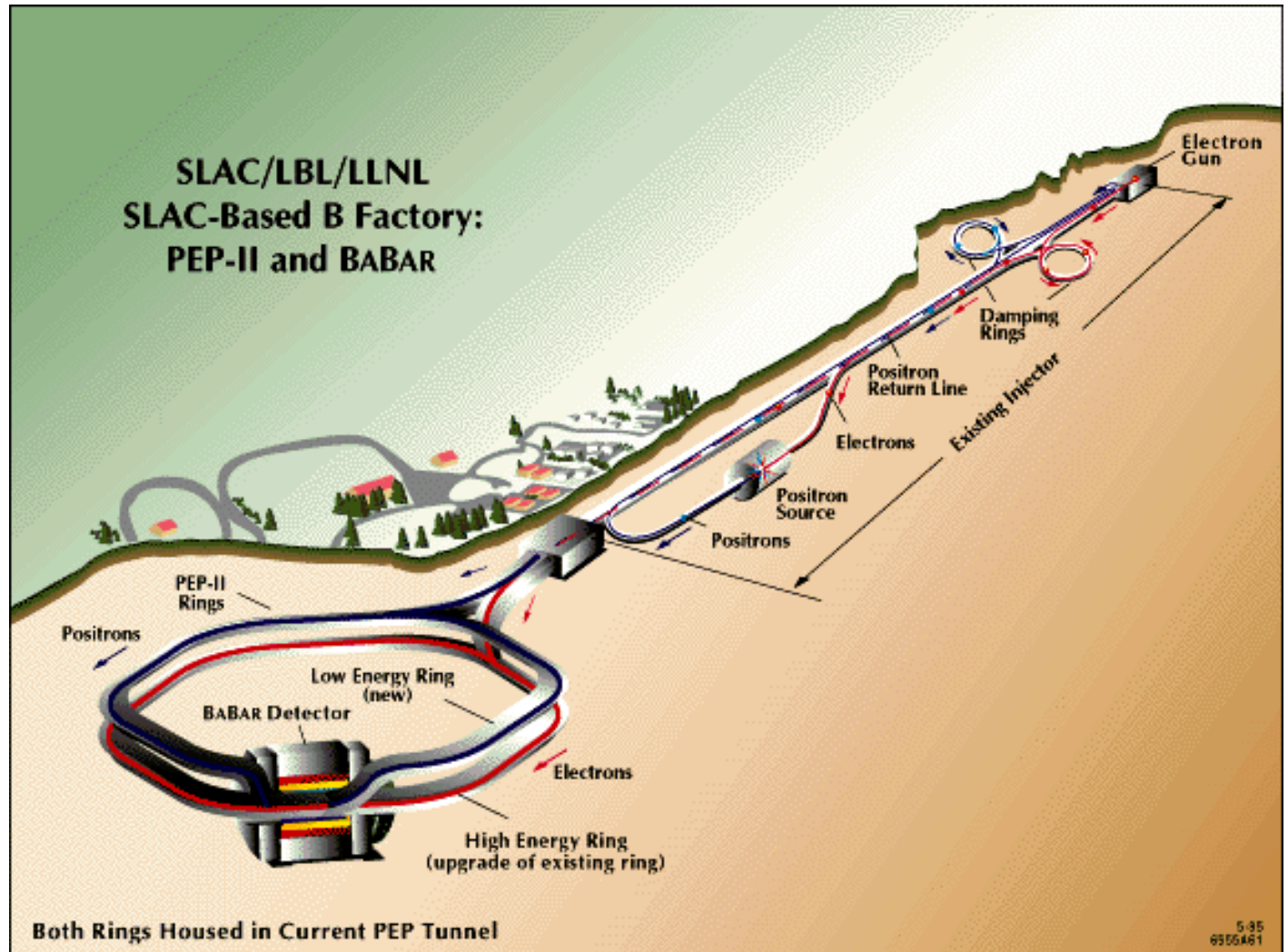


Figure 4-1. The overall PEP-II configuration. (Drawing courtesy SLAC)

Using asymmetric collisions of stored beams with a center-of-mass energy at the Upsilon ( $4S$ ) resonance was originally suggested in 1987 by LBNL Deputy Director Piermaria Oddone. The Upsilon ( $4S$ ) decays into two  $B$  mesons nearly at rest in the center of mass. However, the center of mass is moving in the laboratory frame of reference at about  $0.5c$ , because one beam has much higher momentum than the other. Therefore, the two  $B$  mesons move along the direction of the higher-momentum beam, and their decays are separated in space (or, equivalently, time).

This separation permits the reconstruction of the individual  $B$  mesons and the study of the time evolution of their decays.

*Reported by Michael S. Zisman*

## A Technical Introduction to PEP-II

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PEP-II has two storage rings in the same tunnel, as shown in Figure 4-2. The high-energy ring (HER) is an upgrade of the PEP electron-positron ring and contains 9-GeV electrons. The LER contains 3.1-GeV positrons. A summary of the main collider parameters appears in Table 4-1. PEP-II uses familiar, conservative single-bunch parameters (bunch current, emittance, rms bunch length, and beam-beam tune shift) along with a vertical beta function of a few centimeters at the interaction point (IP). The main increase in luminosity comes from greatly increasing the number of bunches compared with today's colliders. This implies a large increase in beam current, which in turn implies that the vacuum and rf systems must be considerably improved compared with present practice, and that feedback systems to combat coupled-bunch instabilities are needed.



**Figure 4-2.** Components of the asymmetric  $B$  factory PEP-II in the PEP tunnel at SLAC. The lower magnet is a refurbished PEP dipole used for the HER; the upper raft holds LER components. (Photo courtesy SLAC)

**Table 4-1. Main PEP-II Collider Parameters.**

	LER	HER
Energy, $E$ [GeV]	3.1	9
Circumference, $C$ [m]	2199.32	2199.32
$\epsilon_y/\epsilon_x$ [nm·rad]	2.0/66	1.5/49
$\beta_y^*/\beta_x^*$ [cm]	1.5/50.0	2.0/66.7
$\xi_{0x,0y}$	0.03	0.03
$f_{rf}$ [MHz]	476	476
$V_{rf}$ [MV]	5.1	14.0
Bunch length, { EMBED	1	1.15
"Equation" "Word Object1" \* mergeformat } [cm]		
Number of bunches, $k_B$	1658 <sup>†</sup>	1658 <sup>†</sup>
Bunch separation, $s_B$ [m]	1.26	1.26
Damping time, $\tau_E/\tau_x$ [ms]	30.2/62.7	18.3/36.8
Total current, $I$ [A]	2.16	1.00
$U_0$ [MeV/turn]	0.75	3.59
Luminosity, $\mathcal{L}$ [cm <sup>-2</sup> s <sup>-1</sup> ]	$3 \times 10^{33}$	

<sup>†</sup>allows for gap of  $\approx 5\%$  for ion clearing

# Accelerator Physics

## Lattice and Commissioning Issues

In the past year, the lattice work for the LER has mostly been completed. A few minor issues remain, however, and we provide guidance to PEP-II project management as needed. As one example, we have worked closely with the magnet designers at LBNL and IHEP to refine the end-chamfer shape for the LER dipoles. After a number of iterations, an acceptable design was arrived at and validated by tracking at SLAC. Production of these magnets is now under way, and multipole measurements on the first few dipoles at LBNL have confirmed the design. We are also keeping a watchful eye on the relative strengths of the dipoles. It appears presently that the variation is at the limit of our specifications. We are developing a sorting algorithm that can be applied to place the magnets in suitable locations in the lattice. We are also specifying, for the PEP-II engineering staff, the locations of diagnostics devices such as momentum collimators.

We will join SLAC staff in HER commissioning activities, which will be getting under way shortly. Initial commissioning of the LER will begin in September 1997. At that point, it will not yet be possible to store a beam in the ring, but we will test the injection system and bring the beam through one arc (one-sixth of the ring). Full LER commissioning gets under way in April 1998. We are working with SLAC physicists to define the commissioning needs of the LER, particularly in the areas of diagnostics and control system software. We look forward to being closely involved in the continued commissioning of the machine as more systems are brought on line and tested for the first time with stored beam. We expect to participate in pre-operational testing and characterization of the machine, and in the final process of optimizing the luminosity for operations.

*Reported by Alexander Zholents and Michael S. Zisman*

## The Electron-Cloud Effect for the PEP-II Positron Beam

Any intense positively-charged bunched beam creates a cloud of electrons in the vacuum chamber that contains the beam, and this cloud can couple the transverse motion of successive bunches, potentially leading to a multibunch instability. We are actively studying this electron cloud effect for several machines, particularly the low-energy (positron) ring of the PEP-II collider. This effect is a distant cousin of the “beam-induced multipactoring” effect first identified at the ISR 20 years ago.<sup>1</sup> Although it has long been known that an electron cloud inevitably accompanies any positively-charged beam (arising from photoelectrons in the case of a positron beam, or ionization of residual gas in the case of protons), the possibility of a resultant coupled-bunch instability was brought up only in late 1994, by researchers at the KEK Photon Factory (PF)<sup>2,3</sup> who pointed out that this effect can have significant detrimental consequences for intense positron beams with closely spaced bunches. In response to these observations, we have been studying this effect as it applies to the PEP-II positron beam. We plan to explore other machines, such as the LHC, the PSR proton ring, and the projected proton accumulator ring for the NSNS, in appropriate detail.

Using the National Energy Research Scientific Computing Center (NERSC) at Berkeley Lab, we developed a substantial simulation code to study this effect, one of whose central features is careful simulation of the secondary-electron-emission process.<sup>4</sup> The simulation is three-dimensional, and includes the effects of the space-charge force arising from the electron cloud. Though calculations are not complete, interim results show a multibunch instability with a growth time of  $\sim 1$  ms. An instability with such a growth time is well within the range controllable by the feedback system contemplated for PEP-II, but further refinement of simulation input parameters is needed for a more definitive answer. Figure 4-

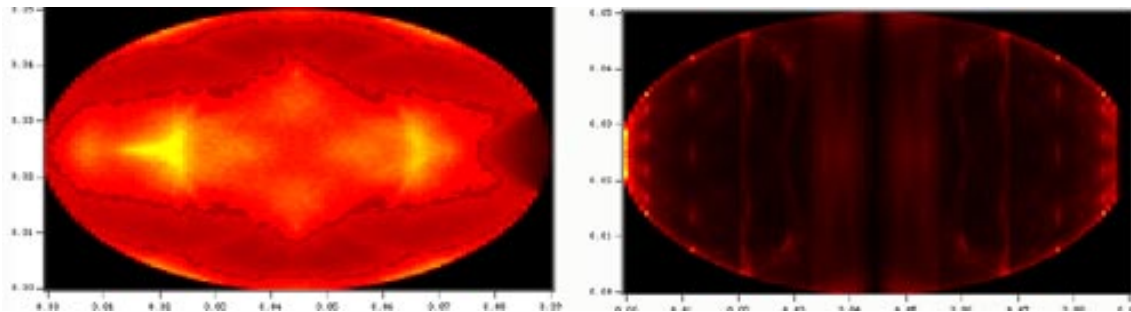
<sup>1</sup> O. Gröbner, “Bunch-Induced Multipactoring,” Proc. 10th Intl. Accel. Conf., Serpukhov, 1977, pp. 277–282.

<sup>2</sup> M. Izawa, Y. Sato and T. Toyomasu, “The Vertical Instability in a Positron Bunched Beam,” Phys. Rev. Lett. **74** (25), 1995, pp. 5044–5047.

<sup>3</sup> K. Ohmi, “Beam Photo-Electron Interactions in Positron Storage Rings,” Phys. Rev. Lett. **75** (8), 1995, pp. 1526–1529.

<sup>4</sup> M. A. Furman and G. R. Lambertson, “The Electron-Cloud Instability in PEP-II,” Proc. EPAC96, Barcelona, Spain, 10–14 June 1996, pp. 1087–1089.

3, obtained from this code, shows the density of the electron cloud in a pumping straight section and in a dipole bending magnet.



**Figure 4-3.** Density plot of the electron cloud. Left: pumping straight section. Right: dipole bending magnet. The beam orbit is at the center of the ellipse. The antechamber slot of full height 1.5 cm (not shown) is at the right side of the chamber. The full scale is 5 by 9 cm in each case.

*Reported by Miguel A. Furman and Glen R. Lambertson*

## Beam-Beam Interaction in PEP-II and in the Muon Collider

We are also studying, by means of simulation, several aspects of the beam-beam effect. We have carried out a fairly detailed study of the expected luminosity performance of the PEP-II collider with the code TRS, which is optimized to study the core of the beam, and have thereby identified the areas in the tune plane where the machine would perform optimally.<sup>5</sup> In collaboration with S. Krishnagopal of Indore, India, we are now developing a particle-in-cell (PIC) code, called CBI, to carry out more accurate calculations than TRS.<sup>6</sup> This new code is much slower than TRS but has the advantage that it can identify single-bunch coherent resonance effects. These resonances are detrimental to luminosity, and it is therefore of practical interest to learn the conditions under which they appear. Present expectations are that they will not materialize under nominal operating conditions for PEP-II.

Another beam-beam effect that may appear in the PEP-II collider, at least during the commissioning stages, is the excitation of multibunch coherent dipole oscillations. This effect is generic to all colliders whose beams are composed of bunches sufficiently closely spaced that parasitic collisions occur in the neighborhood of the interaction point. It is generally believed to be the mildest of the beam-beam effects and thus the least likely to limit machine performance. Nevertheless, it is important to understand it for smooth commissioning of the machine. A code that was developed to study the same problem in the SSC<sup>7</sup> is available but needs to be augmented and generalized to accommodate the

<sup>5</sup> M. A. Furman and J. R. Eden, "Beam-Beam Effects for the PEP-II B Factory," Proc. Part. Accel. Conf., Washington, DC, May 17–20, 1993, p. 3485.

<sup>6</sup> S. Krishnagopal, "Luminosity-limiting Coherent Phenomena in Electron-Positron Colliders," Phys. Rev. Lett. vol. 76, 1996, p. 235.

<sup>7</sup> M. A. Furman, "Results of Coherent Dipole Beam-Beam Interaction Studies for SSC Lattices," SSC-62, May 1986.



asymmetric nature of the PEP-II beams and the more complicated IR optics; these tasks will be carried out this year at the Center for Beam Physics.

We have used both TRS and CBI to study beam-beam effects in the proposed Muon Collider.<sup>8</sup> This machine involves beam dynamics aspects of both a hadron collider and an  $e^+e^-$  collider. The current design calls for round beams at the collision point, with a beam-beam parameter value  $\approx 0.05$ . This value would already be considered rather high for an  $e^+e^-$  collider, and it would be deemed very challenging indeed for a hadron collider. However, the fact that the muon is unstable limits the storage time to  $\sim 1000$  turns in practice. Simulations with TRS that incorporate the finite lifetime of the muon show that, during this short time interval, the emittance of the beam would blow up by only about 5%, and indicate that the average luminosity is limited by the muon decay more than by the beam dynamics. A few runs with CBI also show that coherent effects are not expected to appear.

Although a substantial amount of work shows that impedances and magnet nonlinearities have significant effects on the beam dynamics of this machine, thus far the beam-beam simulation studies have assumed a linear lattice with no impedances. It seems imperative, therefore, to merge these three pieces of dynamics into a single simulation tool. A step in this direction has been taken, by incorporating a "one-turn map" into the code TRS. Thus far, however, only linear (but fully-coupled) maps have been used. We expect that fully nonlinear maps will be incorporated in the near future, and we shall then include them in the beam-beam simulations.

*Reported by Miguel A. Furman*

## Feedback and RF Systems for PEP-II

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### Feedback Systems

Control of the longitudinal and transverse coupled-bunch oscillations of the electron and positron beams in PEP-II is crucial to the success of the project. Feedback systems, together with impedance minimization, are required to achieve this goal. Beam Electrodynamics Group members are responsible both for the design and fabrication of the transverse coupled-bunch feedback systems, and, in collaboration with SLAC, participate in the design and fabrication of the longitudinal feedback system. Previous work on beam impedance calculations and on measurements of a test cavity in the Lambertson Beam Electrodynamics Laboratory has determined the dominant driving impedances for the coupled-bunch instabilities.

The coupled-bunch instabilities encountered at the ALS have characteristics similar to those expected for the PEP-II rings. In particular, the growth times of the coupled-bunch modes are of the order of milliseconds or less in both machines. The ALS feedback systems

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<sup>8</sup> W.-H. Cheng, A. M. Sessler and J. S. Wurtele, "Varying Chromaticity: A Damping Mechanism for the Transverse Head-Tail Instability," LBNL-39717, Dec. 1996.

are fully operational and are being used as prototypes for PEP-II. Our experience in building and commissioning the ALS feedback systems has been of great value for PEP-II feedback system designs.

The transverse feedback system receivers, which use signals from pickups in the accelerator vacuum chamber to determine the beam position, have been constructed and are under test in the Lambertson Beam Electrodynamics Laboratory. Tests of the receivers using the ALS beam to simulate B-factory conditions are planned. The orbit-offset-suppression chassis, which operates a feedback loop within the system to suppress signals generated by either an off-axis beam (closed-orbit error) or an imbalance in receiver rf components, is being tested in the laboratory. This system gives an average of 20 dB suppression of these unwanted signals, which could otherwise cause saturation of the 500 MHz analog-to-digital converter used elsewhere in the system. Figure 4-4 shows a completed receiver ready for laboratory tests.



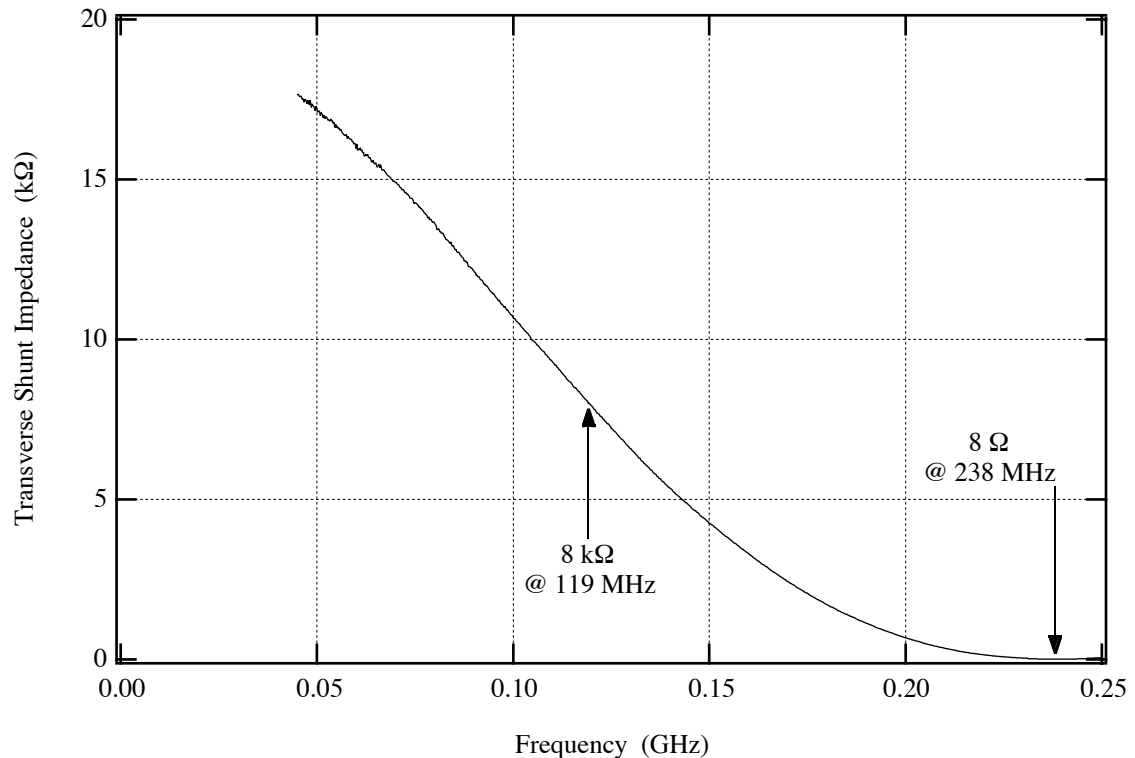
*Figure 4-4. Completed receiver for the PEP-II transverse feedback system. Each receiver takes signals induced by passing bunches in a set of four pickups. Microwave devices in the receiver generate a signal representing the position of each bunch as it passes through the pickups. Deviations of the bunch position are corrected by calculating and applying a compensatory kick signal from position measurements at two points in the storage ring.*

Pickups for both feedback systems have been installed in the PEP-II HER. Stripline kickers, which create electromagnetic fields and provide the transverse kick to the beam, have also been installed in the HER after being measured in the laboratory. During the prototype stage, techniques for damping parasitic modes were developed to minimize the beam impedance and heating of the kickers. These kickers, like the longitudinal feedback kickers built at LBNL, have been blackened using an ion implantation technique to improve



radiative cooling of the electrodes in the vacuum environment of the accelerator. Figure 4-5 shows the measured shunt impedance of the transverse kickers.

Digital electronics to provide a suitable delay between pickup signal and corrective kick, and also to allow particular bunches in the beam to be driven to large amplitude to scrape off some of the charge, are at an advanced design stage. Memory boards have been produced, and the motherboard design is in detailed checking. High-power radio-frequency amplifiers that generate the deflecting kick to correct the beam oscillations have been delivered, tested at LBNL, and shipped to SLAC.

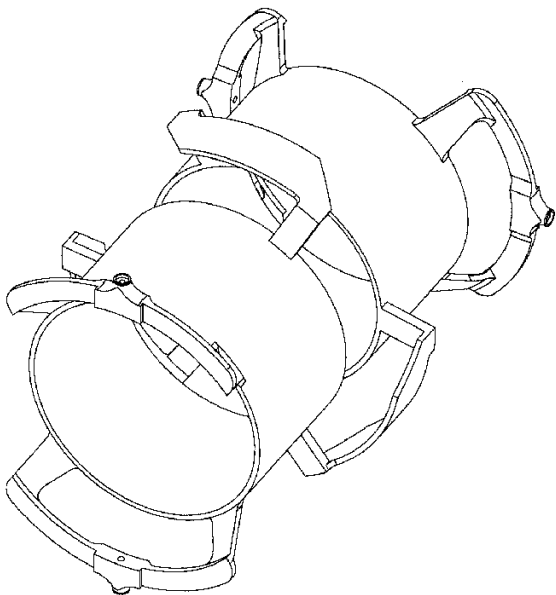


**Figure 4-5.** The measured transverse shunt impedance of the transverse coupled-bunch feedback system kicker. The system operates from 10 kHz to 119 MHz. Though frequencies below 45 MHz are outside the range of the precision network analyzer used for these measurements, the response of the kicker is well predicted at these low frequencies. The kicker changes the momentum of individual bunches at relatively low frequencies, where its efficiency is best.

In addition to the transverse feedback systems, a multi-element longitudinal kicker has been designed for the longitudinal feedback system. This traveling-wave device consists of two coaxial electrodes, connected by delay lines  $180^\circ$  long at the operating frequency, that provide voltages of opposite sign at the ends of the electrodes. This results in doubling the voltage seen by the beam passing along the axis of the device, thereby increasing the efficiency of the structure. Such high-impedance kickers are necessary to provide the voltage kick (several kilovolts) needed in the PEP-II rings at a reasonable cost in high-power

rf amplifiers. The design of the longitudinal feedback kickers is complete for the HER, and the kickers are now installed in the storage ring.

For the LER, the electrodes of the longitudinal feedback kickers are cooled by conduction through beryllia supports, which have little effect on the electrical characteristics of the kicker, but allow good thermal transport. The heating, which arises from beam-induced currents on the surface of the electrodes, is approximately 10 W at high beam current. The LER design is at an advanced stage, with thermal tests already under way. Initial results confirm our predictions and indicate that the beryllia supports will provide a sufficient cooling path. The power generated at the upstream terminals of the longitudinal kicker is appreciable and the vacuum feedthroughs, obtained commercially, are designed to transmit up to 5.5 kW of total rf power at frequencies extending up to 7 GHz. Figure 4-6 shows a 3-D rendering of the kicker electrodes.



**Figure 4-6.** A 3-D rendering of the longitudinal feedback kicker electrode. Note the two cylindrical drift-tubes, connected by delay lines 180° long at the operating frequency. These delay lines ensure opposing voltages on the facing ends of the drift tubes, thereby doubling the voltage seen by the beam passing along the axis of the device. The structures connected to the outside ends of the drift-tubes are to allow power to be fed into the kicker, and power induced by the beam to travel out of the kicker.

As with the transverse feedback kickers, damping of parasitic modes for the longitudinal kicker was developed to minimize the beam impedance and heating of the electrodes. Measurements using the state-of-the-art equipment in the Lamberton Beam Electrodynamics Laboratory and computations using 3-D electromagnetic design codes have been made to confirm the characteristics of these essential rf structures.

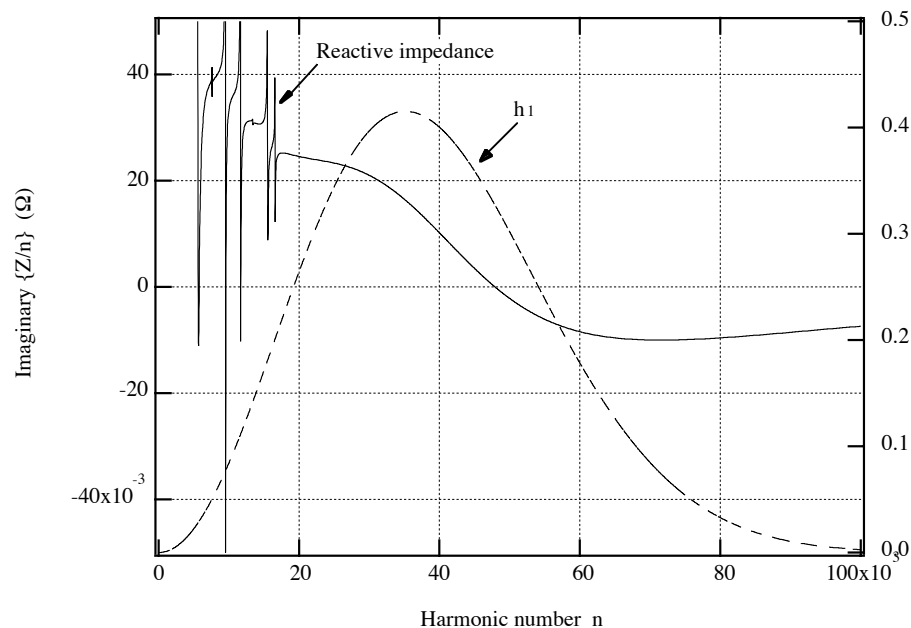
*Reported by John Corlett, Walter Barry, and Glen Lamberton*

## Impedance Measurements and Collective Effects

Cataloging the impedances of components in the vacuum chamber is another ongoing task of the Beam Electrodynamics Group. These impedances give rise to beam instabilities, as the wall currents induced by the beam excite electromagnetic fields that influence the trajectory of following particles. Impedance computations of components have been made with state-of-the-art two- and three-dimensional electromagnetic design codes, and careful measurements are made in the laboratory of prototype components to ensure a low impedance of the machine.

Particular attention has been paid to the design of the rf shielding structures for the bellows, a component that is required in order to allow for thermal expansion (and installation) of other vacuum components. Without an rf shield, the impedance of a corrugated bellows is known to be unacceptable. Spring-loaded sliding fingers have been designed that allow both smooth passage of the beam-induced currents in the accelerator wall and thermal movement of the vacuum chamber. Because such components have intricate structure, careful measurements and computations have been made to provide a high degree of confidence in their successful operation at the high beam currents in the PEP-II storage rings. It is worth noting here that the equivalent component in the ALS, the flexband, has experienced failures on several occasions under conditions less severe than expected for the PEP-II LER, and other machines have had similar problems.

Computations of instability thresholds and collective effects—including simulations of the operation of the feedback systems with realistic machine impedances and under realistic conditions of injection transients—have been updated for the latest impedance estimates and measurements for PEP-II. For rigid-bunch motion, the feedback systems are shown to control the beam motion. Estimates of the broad-band beam impedance, which drives single-bunch instabilities, have been refined. Figure 4-7 shows the calculated reactive impedance for the LER. Single-bunch instabilities are not expected to occur under normal operating conditions.



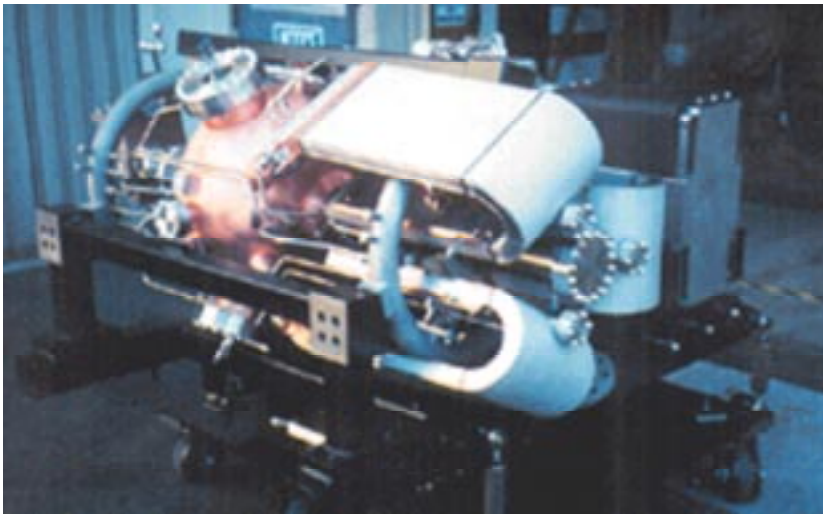
**Figure 4-7.** The reactive impedance of the PEP-II LER, normalized to the orbit frequency ( $n$  is the ratio of frequency to orbit frequency). Also shown is the power spectrum  $h_1$  for the first mode of oscillation within the bunch. The effective impedance is the impedance weighted by the appropriate power spectrum.

*Reported by John Corlett*

## RF System Progress

The rf cavities for the storage rings of the PEP-II project are required to provide high accelerating gradient while supplying high power to the circulating beam. This presents many challenges in the design of the cavities themselves, as well as ancillary components such as windows and tuners. At the same time, because of the high average current and large number of bunches, there is particular sensitivity to the impedances of higher-order modes (HOMs) in the cavities, which can drive coupled-bunch instabilities.

In PEP-II, these conflicting requirements are addressed by using efficient and rugged copper re-entrant cavities with the addition of three special HOM-damping waveguide loads (Figure 4-8). The waveguides open into the body of the cavity and allow the beam-driven higher-order modes to propagate out and dissipate harmlessly in the loads. Their design has been optimized to make best use of the absorbing material and to fit into the limited space available in the tunnel.



*Figure 4-8. The PEP-II rf cavity accelerates the beam with the fundamental mode while diverting the disruptive higher-order modes into external loads that absorb the microwaves.*

The design concept for these heavily-damped structures came from the Center for Beam Physics (see the previous chapter), which has been actively involved in the development of the rf systems for PEP-II. The damping waveguides are folded so that the loads are “tucked in” parallel to the beam pipe. The cavity, coupler, and load assembly are pre-aligned and tested on a raft before installation in the tunnel. This damping scheme was proved to be very effective by a series of measurements on a cold-test model in the Lambertson Beam Electrodynamics Laboratory here at Berkeley Lab. With the success of this model, the PEP-II rf group, drawing upon resources from SLAC and LLNL as well as Berkeley Lab, designed a full-power version with only minor changes to the geometry. The major challenges in the design of the high-power cavity were thermal management: to efficiently dispose of the power from wall losses and to minimize stresses in the cavity body. The cooling scheme was

optimized with sophisticated three-dimensional finite-element, rf, thermal, and stress analyses.

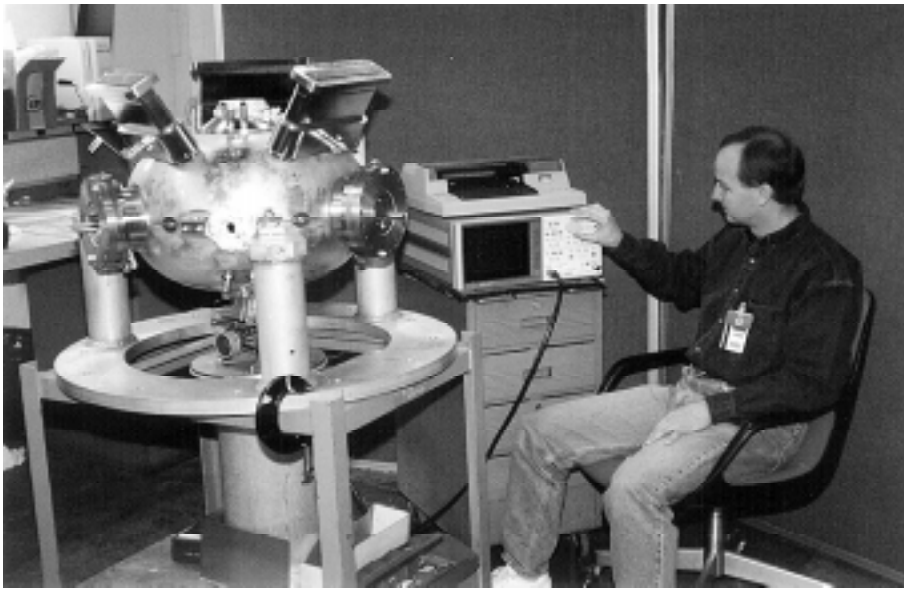
The high-power cavities are now in production, and tests have verified the designs developed over the past few years. Production cavities have been tested up to full LER power (105 kW), developing an accelerating voltage of 850 kV. The high-power test cavity was run up to 120 kW at SLAC with a few excursions to higher power for short periods. All critical components of the design have performed well.

Measurements of a production cavity have been made in order to accurately determine the impedance presented by the rf cavity HOMs. This information is needed in determining the minimum power and gain needed for the coupled-bunch feedback systems, and has been incorporated in the latest calculations of beam instabilities.

The rf system work in general is at an exciting stage, with production of components and systems in full swing and large scale assembly and installation taking place in the tunnels and support buildings. We continue to be involved in many areas of the rf systems, including the manufacturing and testing of rf cavities and, in particular, the final frequency tuning and UHV cleaning operations at LLNL, prior to final shipment to SLAC (see Figure 4-9). We also assist with the high-power testing of completed cavity assemblies at SLAC and have actively participated in the commissioning of the first installed stations for the HER. We participate in production planning and help to overcome any technical problems that arise. And we have maintained our interests in the design and production of other components, such as the high-power windows and tuner assemblies, although the principal responsibilities for those activities belong to others in the collaboration.

We have continued to study the issues of machine impedance and collective effects with regard to the rf systems. For example, we have looked at the thresholds for higher-order ( $m = 1$ ) coupled-bunch modes that are less well damped and might be driven by the residual cavity impedances. We have developed conceptual schemes to further reduce the driving impedances for these modes should this prove necessary.

*Reported by Bob Rimmer*



*Figure 4-9. Tuning of production rf cavity at Lawrence Livermore National Laboratory by LBNL physicist Bob Rimmer. Final welding of the cavity is completed after this step.*